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TECHNICAL PROPOSAL

D1-82-1042

ANALYSIS OF GROUND OPERATIONS AT AIRPORTS

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In Response to

Request for Proposal WA5R-1-0246

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TABLE OF CONTENTS

	Page
1.0 Introduction	1
2.0 Background and Objectives	1
3.0 Method of Approach	3
3.1 Inventory	4
3.2 Models	7
3.3 Measurements	8
3.3.1 Carbon Monoxide	8
3.3.2 Hydrocarbons	19
3.3.3 Particulates	20
3.3.4 Oxides of Nitrogen	21
3.3.5 Meteorology	22
3.4 Instrument Deployment and Model Validation	23
3.5 Operational Procedures	27
4.0 Major Problem Areas and Solutions	30
4.1 Calculational Problems	30
4.2 Experimental Problems	31
4.3 Interaction between Measurement and Models	31
5.0 More Detailed Discussion of the Model	33
5.1 A Gaussian Plume Model	33
5.2 A Time Dependent Model	35
6.0 Program,Schedule, Reports, and Time Estimates	37
6.1 Schedule	37
6.2 Reports	37
6.3 Time Estimates	40
7.0 Professional Talent, Consulting, and Related Experience	40

TABLES

		Page
Table 1	FAA Reported Flight Activities for the First Ten Months of 1970.	5
Table 2	Contributions of an Aircraft and Automotive Transport to Airport Pollution.	6
Table 3	Table of Instruments for Pollution Measurements.	18
Table 4	Meteorological Instruments.	23
Table 5	Twenty-Four Hour Measurement Schedule.	25
Table 6	Jet Exhaust Parameters.	35

FIGURE CAPTIONS

		Page
Figure 1	Carbon Monoxide Source Inventory for a Simulated Airfield.	9
Figure 2a	Steady-State Ground-Level Contour Map of Log_{10} $[X_{CO}]_{ppm}$, fot Taxi and Service, Idle, and Flight Operations.	10
Figure 2b	Isometric Plot of the Same Contour Map as 2a.	11
Figure 3	Isometric Plot of $\text{Log}_{10}[X_{CO}]_{ppm}$, for Taxi and Service Operations.	12
Figure 4	Isometric Plot of $\text{Log}_{10}[X_{CO}]_{ppm}$, for Idle Operations Only.	13
Figure 5	Isometric Plot of $\text{Log}_{10}[X_{CO}]_{ppm}$, for Flight Operations.	14
Figure 6	Isometric Plot for Same Conditions as 2a and 2b, but Computed by the Time-Dependent Model.	15
Figure 7	Isometric Plot for an Intermittant Point Source of 1 kg/sec Having a 1/7 Duty Cycle.	16
Figure 8	Isometric Plot for a Point Source of 1 kg/sec with Oscillatory Winds.	17
Figure 9	Work Schedule - Months After Go-Ahead	38
Figure 10	Functional Organization Chart	39

1.0 Introduction

The Boeing Company, Boeing Scientific Research Laboratories, proposes a 12-month technical effort in response to the RFP WASR-1-0246 entitled "Analysis of Ground Operations at Airports." This effort will be divided into three separately definable tasks entitled 'Investigation and Model Development,' 'Model Validation,' and 'Model Extension.' A work schedule for each of these tasks is given in Section 6.0.

The technical discussion is not, however, separated according to these three tasks but is given in the more general format requested. Accordingly, in the Section 2.0 entitled 'Background and Objectives' the subject of airport ground operations and concomitant pollution is introduced. Relevant background material is cited and the objectives of the study are defined.

In Section 3.0 entitled 'Method of Approach,' means of achieving these objectives are given. These include procedural studies for minimizing pollutant emissions, the compilation of an inventory of pollutant sources, the development, use, and extension of an existing mathematical model to describe atmospheric dispersion mechanisms, and model iteration and verification with data obtained in a field measurement program. Section 4.0 contains a discussion of major problem areas. Finally, additional information on the mathematical model is presented in Section 5.0.

The remaining Sections 6.0 and 7.0 deal with scheduling, and with professional capability and background experience, respectively.

2.0 Background and Objectives

Airports currently contribute only about 1% of the total air pollution burden in urban environments[1]. In terms of emissions per unit land area the source fluxes of hydrocarbons, nitrogen oxides, carbon monoxide, and suspended particles generated at airports are

comparable to those of adjacent suburbs(1). However, airport pollution is not distributed uniformly. For example, dense sequences of aircraft landing and rising, usually parallel to the wind, distribute their exhausts in a narrow vertical sheet whose lateral dispersion can be relatively slow(2). Thus the most severe air pollution by particulates is experienced in localized areas. Pollution from aircraft and airports is likely to become more significant because of a growth in air traffic(1), and a concurrent reduction of urban emissions resulting from stricter pollution controls on ground vehicles and stationary sources.

A reduction in airport generated pollution can be achieved through improved engine design and revised ground operational procedures. Progress is being made in engine design. The recent JT9D (used on the 747) emits per lb of fuel less than 70% of the CO, and less than 10% of the hydrocarbons emitted by the JT3D (used on the 707). The particulate emission has also been reduced as is evidenced both by engine test data and visual observation at take-off. Modifications, such as the introduction of 'smokeless burner-cans' on the JT8D-7 (used on the 727) have also reduced particulate, CO, and hydrocarbon emissions.

Current ground operational procedures have evolved to be functional, economical, and convenient, but not to be minimally polluting. For example, airline schedules have been established which, for economic advantage, cluster departures at peak traffic hours, thereby producing queues of aircraft at idle. It is in the idle and taxi modes that jet engines mainly contribute to CO and hydrocarbon pollution.

In this proposal we discuss the manner in which airport ground operations can most effectively be changed to minimize pollution. Ground operations will be analyzed and proposed changes will be evaluated in terms of their cost, practicality, pollution reduction, and convenience. The effect of these changes on pollution levels at and near the airport will be assessed using a mathematical model. This

model will be made flexible for nationwide application and will be programmed for use by the FAA, or other personnel, with explicit instructions to aid data control and interpretation. The model will be validated by a measurement program.

Boeing personnel to be engaged in this program have extensive experience in airport operations and procedures, in atmospheric modelling, and in experimental methods. Two consultants, Drs. R. Charlson and J. A. Fay, will be engaged to provide further experience in meteorology and airplane pollution control.

3.0 Method of Approach

An evaluation of the air quality at major airports across the nation could be made from *in situ* measurements. However, such a program would be expensive and would give little guide to the effect of future changes of pollution sources. Such a guide is potentially available, however, at lower cost through the use of a mathematical model formulated to compute the pollution concentrations at any airport, incorporating local meteorological and pollution source data. To establish such a model it is necessary to formulate the mathematics, insert source data, and verify the results by actual measurements. It is proposed that this be done at both Dulles International and Washington National Airports. These airports have dissimilar ambient pollution levels, aircraft type distribution, flight schedules, and ground operational procedures. They will provide a good test of the versatility of any model. We shall discuss the modelling under the following headings: inventory (3.1), mathematical formulation (3.2), measurements (3.3), and model test and verification (3.4). This section will end with a discussion of operational procedures (3.5).

3.1 Inventory

A pollution source inventory for ~~an~~ airports ~~must~~ include airplane operations (categorized according to taxi, idle, take-off, and landing), aircraft support vehicle operations, vehicular movements, stationary power and heat-source operations, and fueling operations. We discuss these components below.

The airplane contribution to pollution depends upon the engine type and mode of operation. Reciprocating engines emit about the same pollution per pound of fuel as automobile engines used in a fuel-rich mode with no pollution control systems. The effect of the rich mixture is to cause high emission of CO and hydrocarbons. Jet engines, when operated under optimum design conditions (cruise operation, for instance) are notable clean. Unfortunately, the ground operations of idle and taxi are far from optimum. At idle the JT8D-7 engine with smoke reducing burner cans emits, per pound of fuel, more than 50 times the CO emitted at cruise. For hydrocarbons this ratio exceeds 200. Oxides of nitrogen behave in the opposite fashion, however; the emission per pound of fuel at idle is about one quarter that at take-off. Thus, a change in ground-operation procedures which would operate jet engines closer to thrust optimized conditions would reduce CO and hydrocarbon emissions, but increase emissions of nitrogen oxides.

Since jet engine emissions depend heavily on the mode of operation, airline schedules alone are not sufficient for a good estimate of the pollution emitted. Queuing at major airports is a well-known phenomenon and occurs frequently at Washington National Airport. At peak traffic periods, we will provide observers to follow the queuing operations. We will also evaluate the use of time-lapse photography for this purpose. We will obtain an operational inventory of general and military activities. This is particularly necessary at Dulles where these activities exceed carrier flights. See Table 1.

Table 1. FAA Reported Flight Activities for the First Ten Months of 1970 (in thousands of operations)

Airport	Carrier	General	Military
Dulles	52	72	31
National	178	89	3

In contrast to aircraft queuing, touch-and-go and practice approach operations will contribute little to the total pollution.

Careful attention to airplane-support vehicle operations is required, both to estimate an inventory at each airport and to project the effects of changes in this inventory. Most support vehicles are powered by either a gasoline or diesel internal combustion engine, which have well known characteristics. Support operations are described in service manuals and current practice will be confirmed through the airlines.

The importance of the contribution of vehicular traffice to airport pollution is illustrated by the following estimate. At the Seattle-Tacoma Airport, 1969 figures indicate that one vehicle entered the airport for each 1.5 passengers passing through. Consider one 727 landing with 90 passengers, and assume that its emissions of CO and hydrocarbons are given by the idling characteristics of its three JT8D-7 reduced smoke burner engines. Make the futher assumptions that the mean speed of the automobiles is 10 mph and that the automobiles are driven for an average time equal to the landing and taxiing time of the airplane. Then, using the rates of emission given in Table 2, it is clear that the automobile emissions (from vehicles without pollution control devices) of CO and hydrocarbons are comparable to those of the airplane. Vehicular traffice constitutes an important source of airport pollution.

Table 2. Contributions of an Aircraft and Automotive Transport to Airport Pollution(3)

Three JT8D-7 jet engines at idle with Reduced Smoke Burner Cans (727)	CO 181 lbs/hr Hydrocarbons 34 lbs/hr
60 autos at 10 mph (without pollution control devices)	CO 210 lbs/hr Hydrocarbons 18 lbs/hr

The volume of vehicular traffic will be obtained from surveys, and parking lot and garage records. Comparisons will be made with other airports for which information is available.

Emissions from stationary power systems, including SO_2, will be calculated on the basis of the quantity and type of fuel consumed and the established characteristics of these pollution sources.

Fuel spills and losses by evaporation will be estimated for use in the hydrocarbon pollution inventory.

The discussion has so far dealt with the contribution to airport pollution from local sources. There are additional contributions from adjacent urban areas. Information on background urban pollution levels will be obtained from Community Air Monitoring Program (CAMP) stations, other stations maintained by local authorities, and from local studies. During slack periods at the airports, such as between midnight and 6:00 a.m. at National, when there is only one scheduled flight, we shall measure background levels. These backgrounds will, of course, vary with time. If local data are insufficient to describe this

variation we will use existing records for guidance and, for part of the study, we will place instrumentation at a location which is representative of background conditions.

3.2 Models

Having established the strengths, spatial and temporal distributions of the pollutant sources, a mathematical dispersion model will be used to derive contour maps of individual pollutant concentrations. Reviews of mathematical models have been written by Moses[4], Neiburger[5], Turner[6], Reiquam[7], and others, and simplified models have been applied to idealized airfield runways[8]. Most models employ variants of the "gaussian plume" to estimate downwind dispersion from point sources. Area sources are treated by summing contributions from distributed point sources. Transverse and vertical mixing coefficients are estimated from wind-direction fluctuations, or more often are taken from convenient empirical tables[6], or treated as adjustable parameters to maximize the fit between computed and measured concentrations[6,9]. This family of models gives time-independent solutions for particular source strengths and wind conditions. If desired, these solutions can be averaged over a distribution of wind strengths and directions. These models are conceptually pleasing, easy to use, display fair correlation with time-averaged measurements, and present their results in a form suitable for an air quality survey. Corrections for meteorological inversions and plume buoyancy are straightforward, but at low wind speeds and small scale length the circulatory wind meanderings are not simply interpretable as gaussian. To our knowledge no model successfully includes wave instabilities concomitant to stratified flows, which are important for a description of ground-fumigation events occurring when inversions break up. However, the fumigation problem itself has been treated[6]. Due to the importance of decisions

to be based on the model constructed for this study and because computing expenses will not be a major part of the costs, we prefer to begin with a model of adequate complexity. We have formulated such a model and provide a more detailed description of it in Section 5.0 of this proposal. To demonstrate the use of this dispersion model we have constructed an inventory and schedule of pollutant injections for a simulated airfield. In Figures 1 through 8 we show a simplified time and space averaged source map and concentration contours for CO at peak traffic conditions. It can be seen that for the assumed traffic and wind conditions peak CO concentrations of about 10 ppm are predicted.

3.3 Measurements

To refine and establish the models described above and in Section 5.0, we will measure pollutant levels on and around Dulles and Washington National Airports. The pollutants of concern are CO, hydrocarbons, particulates, and nitrogen oxides. Some general comments on each of these pollutants are given in Sections 3.3.1 - 3.3.4. Also necessary are the measurements of local meteorological conditions described in Section 3.3.5. The pollution monitoring and meteorological instruments we will use in this study are listed in Table 3 and 4.

3.3.1 Carbon Monoxide

While the background level of CO in the lower atmosphere is of the order of 0.1 ppm, the concentration in urban regions is considerably larger. In the Washington, D.C. area, mean concentrations were 5 ppm February through August of 1967[10]. The concentration in the vicinity of Dulles, which is in a rural environment, is considerably less than 5 ppm and its measurement requires sensitive instrumentation.

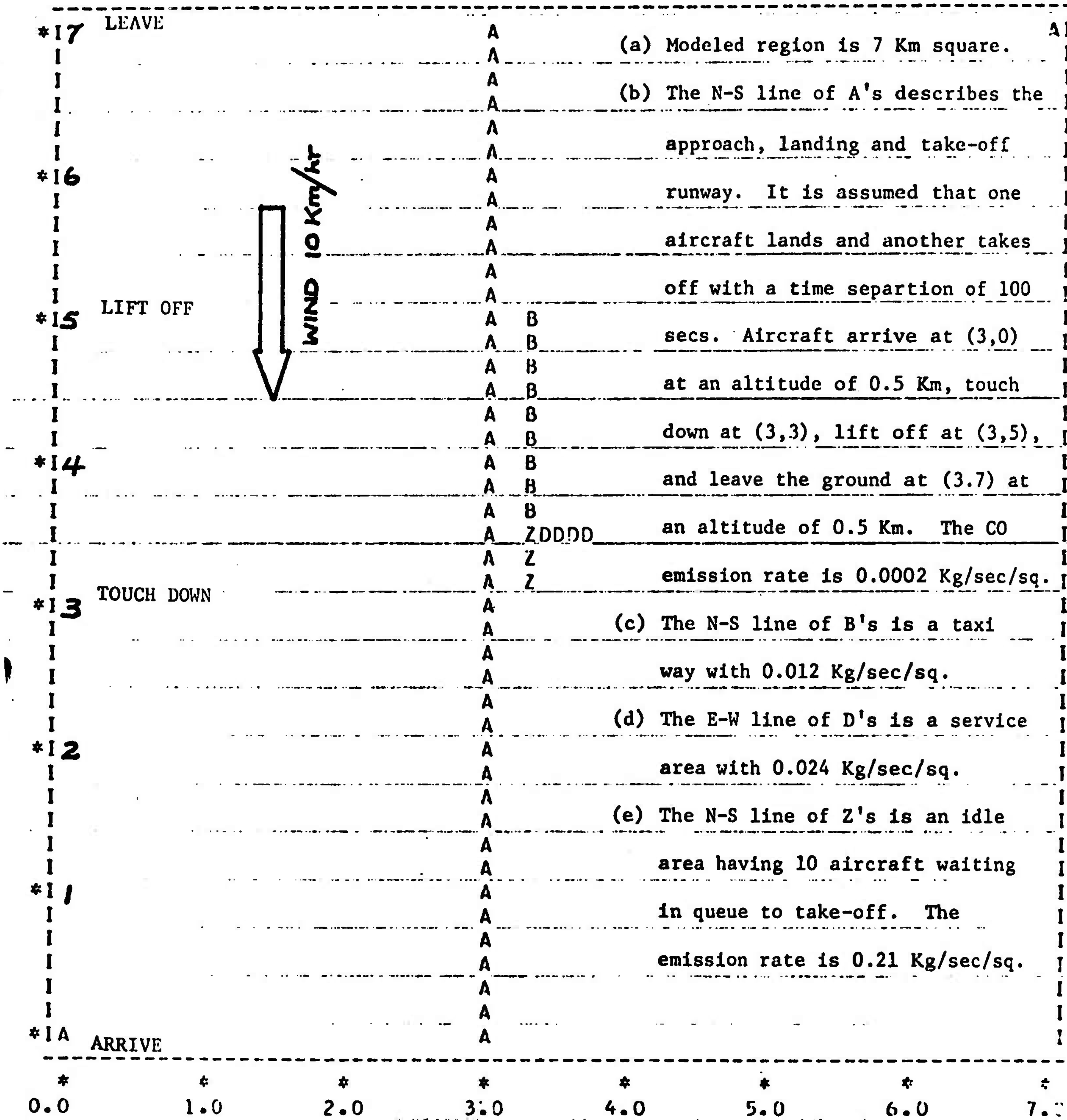


Figure 1. Carbon Monoxide Source Inventory for a Simulated Airfield

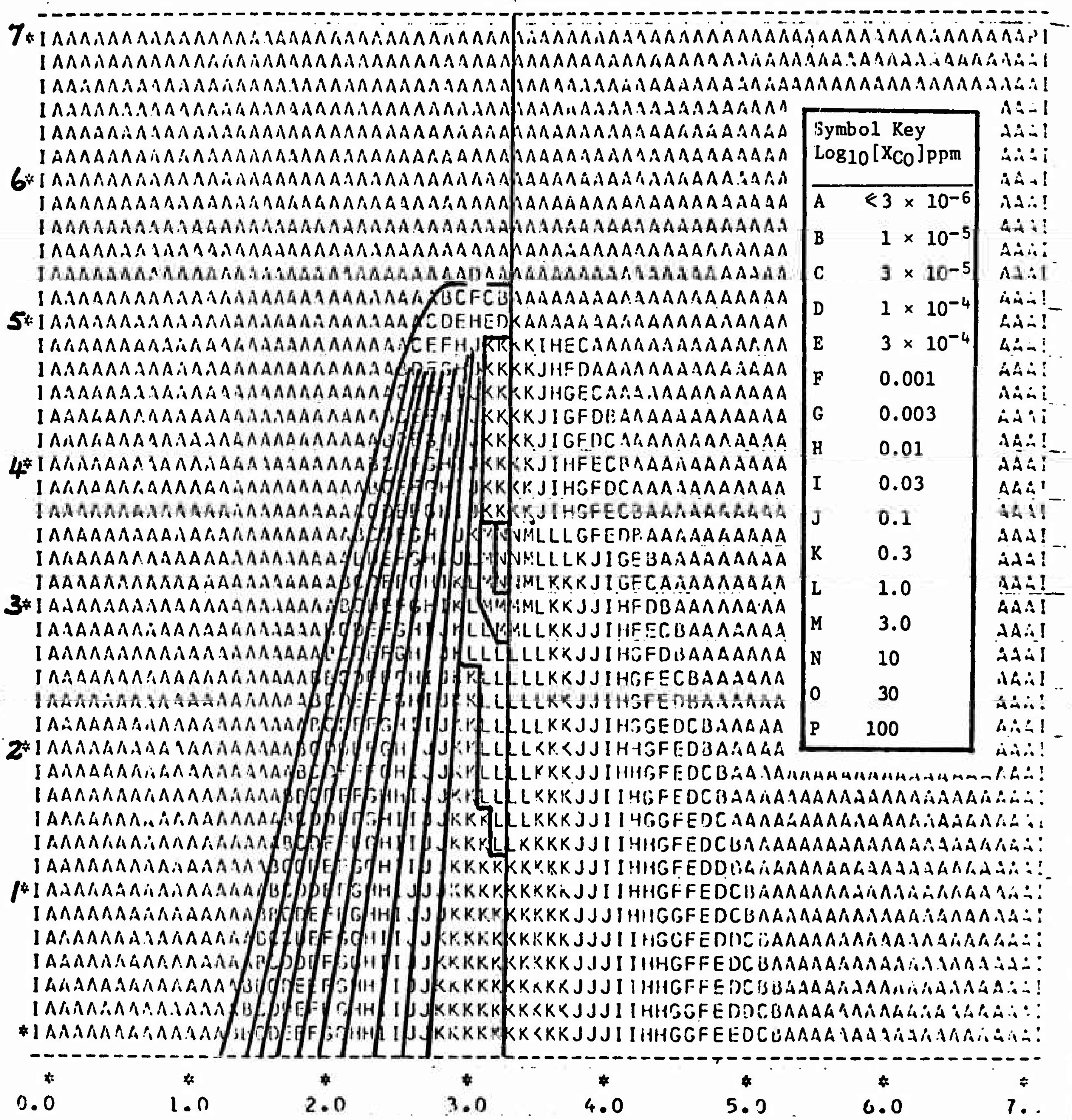


Fig. 2(a). Steady-state ground-level contour map of $Log_{10}[X_{CO}]$ ppm for taxi, service, idle, and flight operations (all symbols of Fig. 1). Wind is 10km/hr from the N. It can be seen that the highest computed concentration is 3 - 10 ppm, averaged over a single grid element [100 x 167 m]. For this and the following plots, no inversion is assumed. Plume buoyancy is included in this model; jet wake disturbance is not. The concentration contours shown schematically on the left-hand side of this figure can be automatically generated.

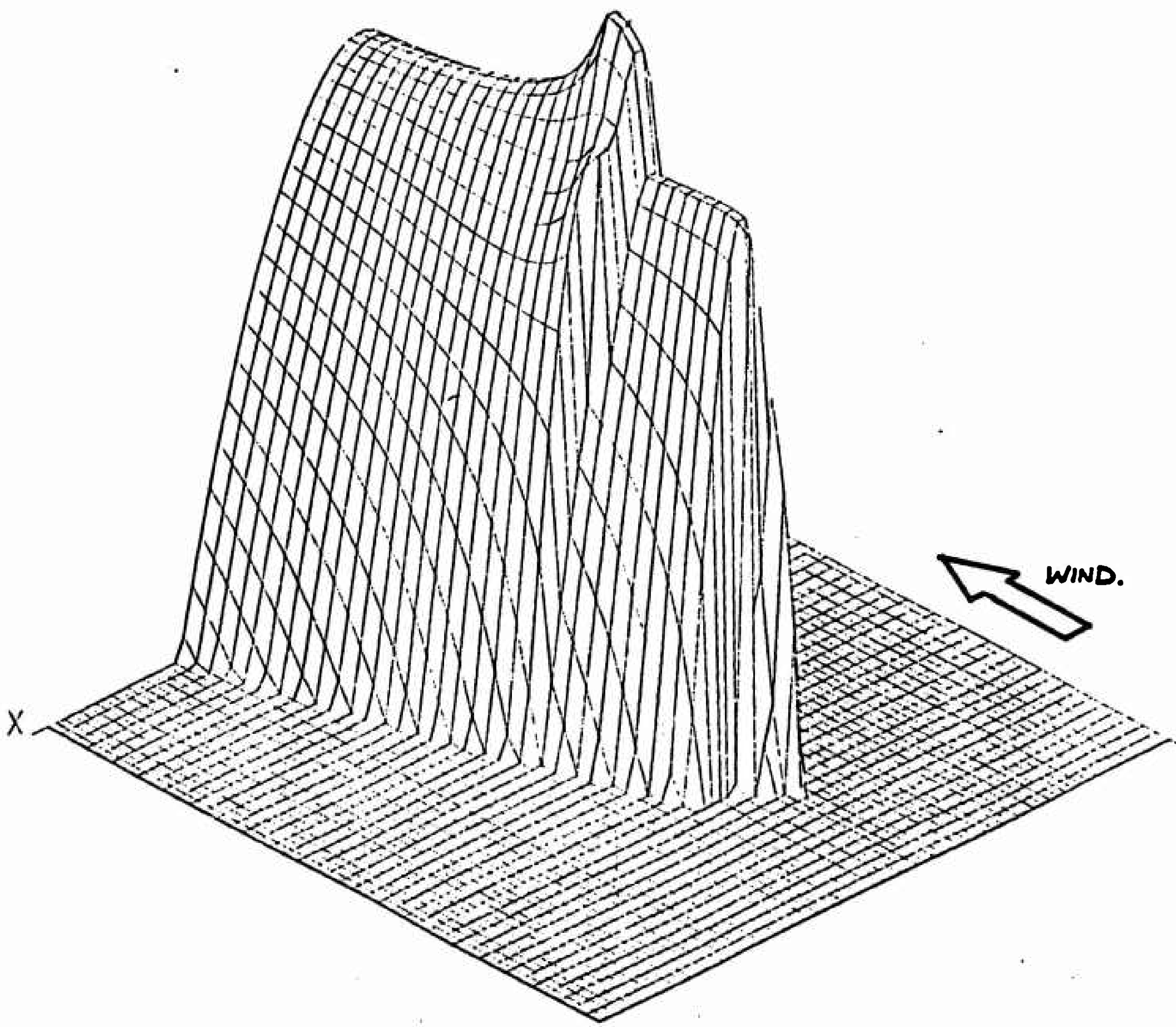


Fig. 2(b). Isometric Plot of $\text{Log}_{10}\left[X_{co}\right]$ ppm for taxi, service, idle, and flight operations. Peak concentration is 3-10 ppm. View is from NE toward SW.

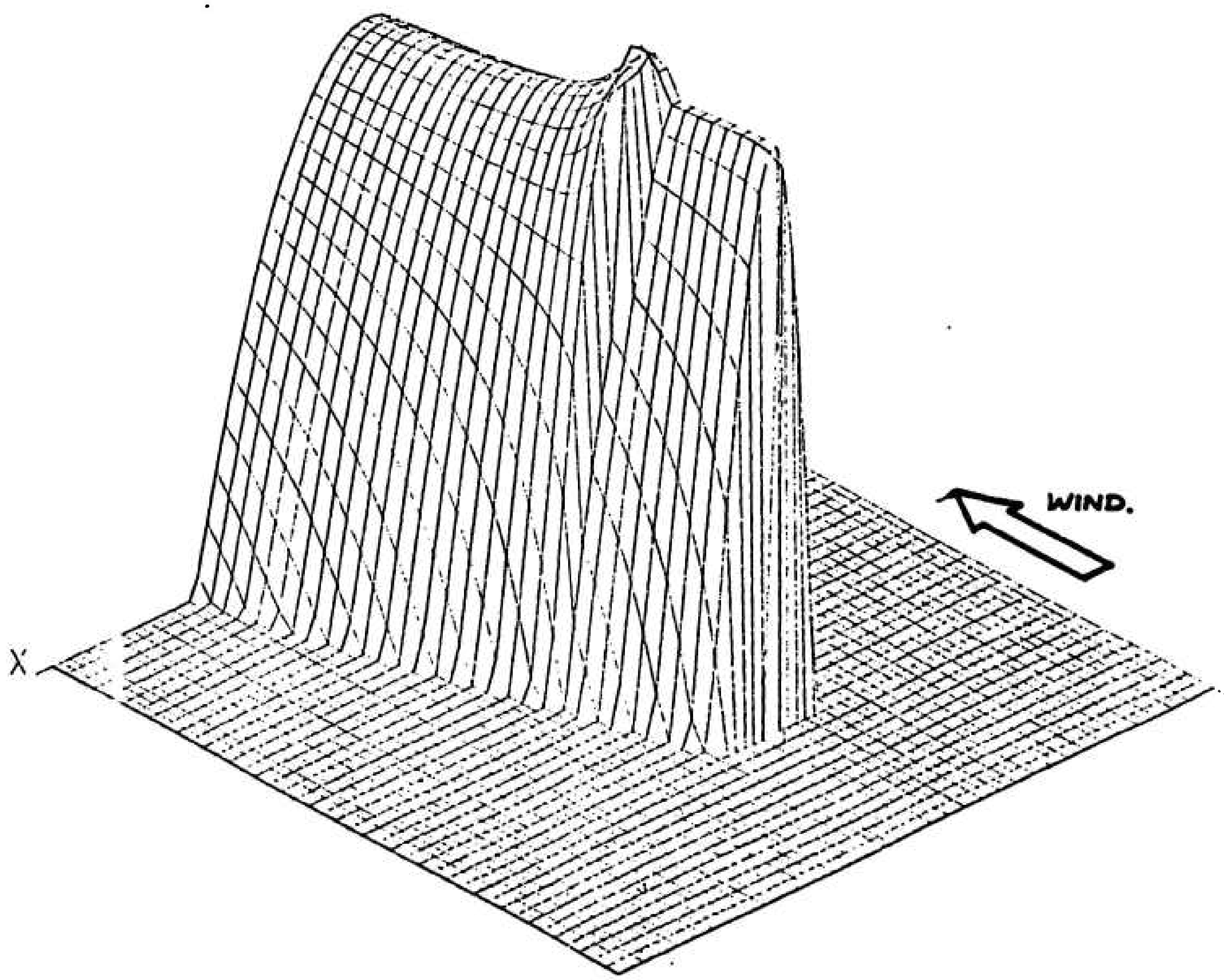


Fig. 3. Isometric Plot of $\mathrm{Log}_{10}[X_{CO}]_{ppm}$ for Taxi and Service, Operations Only [B's and D's of Figure 1]. Peak Concentration is 1-3 ppm.

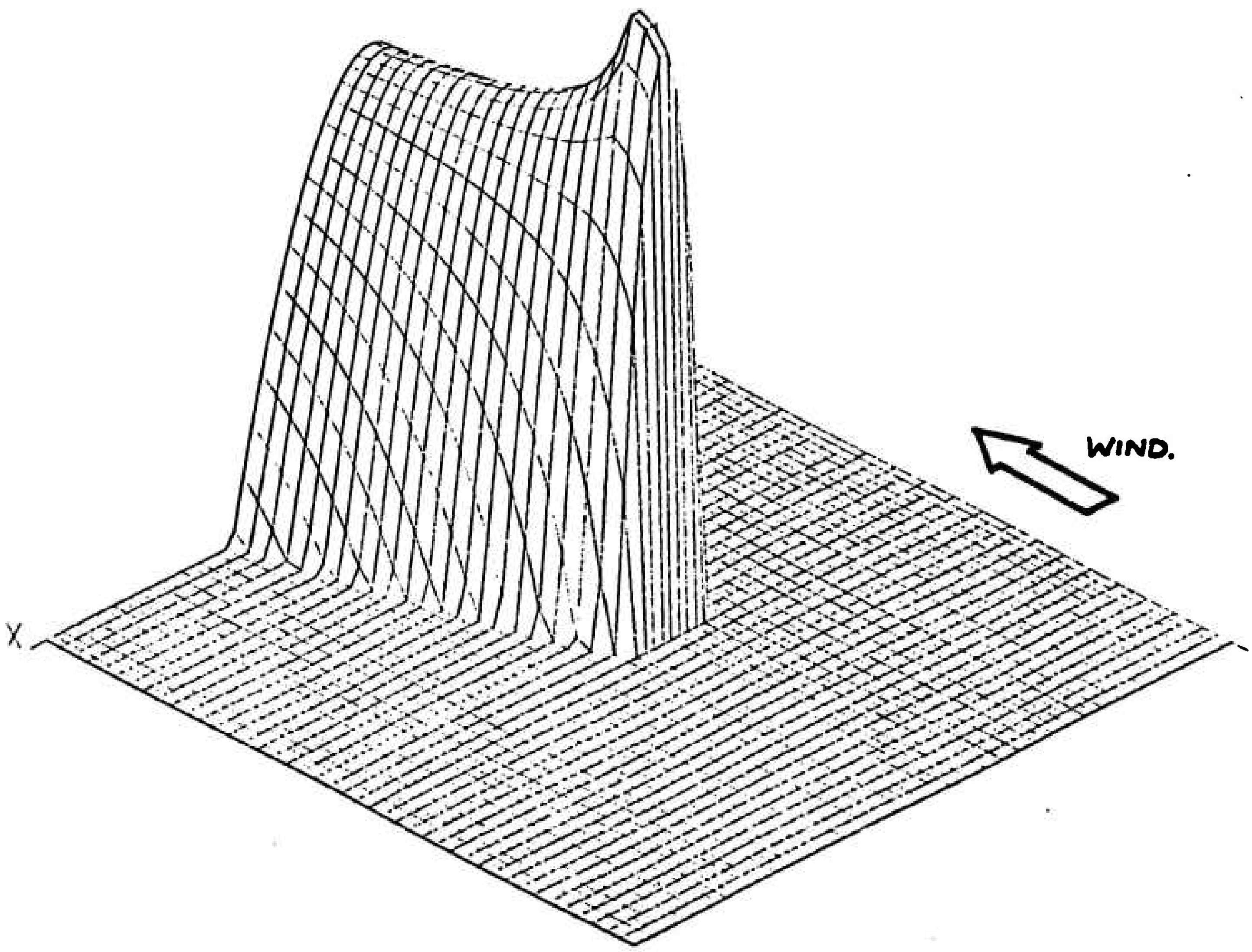


Fig. 4. Isometric Plot of $Log_{10}[X_{CO}]_{ppm}$ for Idle Operations Only [Z's of Figure 1]. Wind Speed is 10 Km/hr, for the N Peak Concentration is 1-3 ppm.

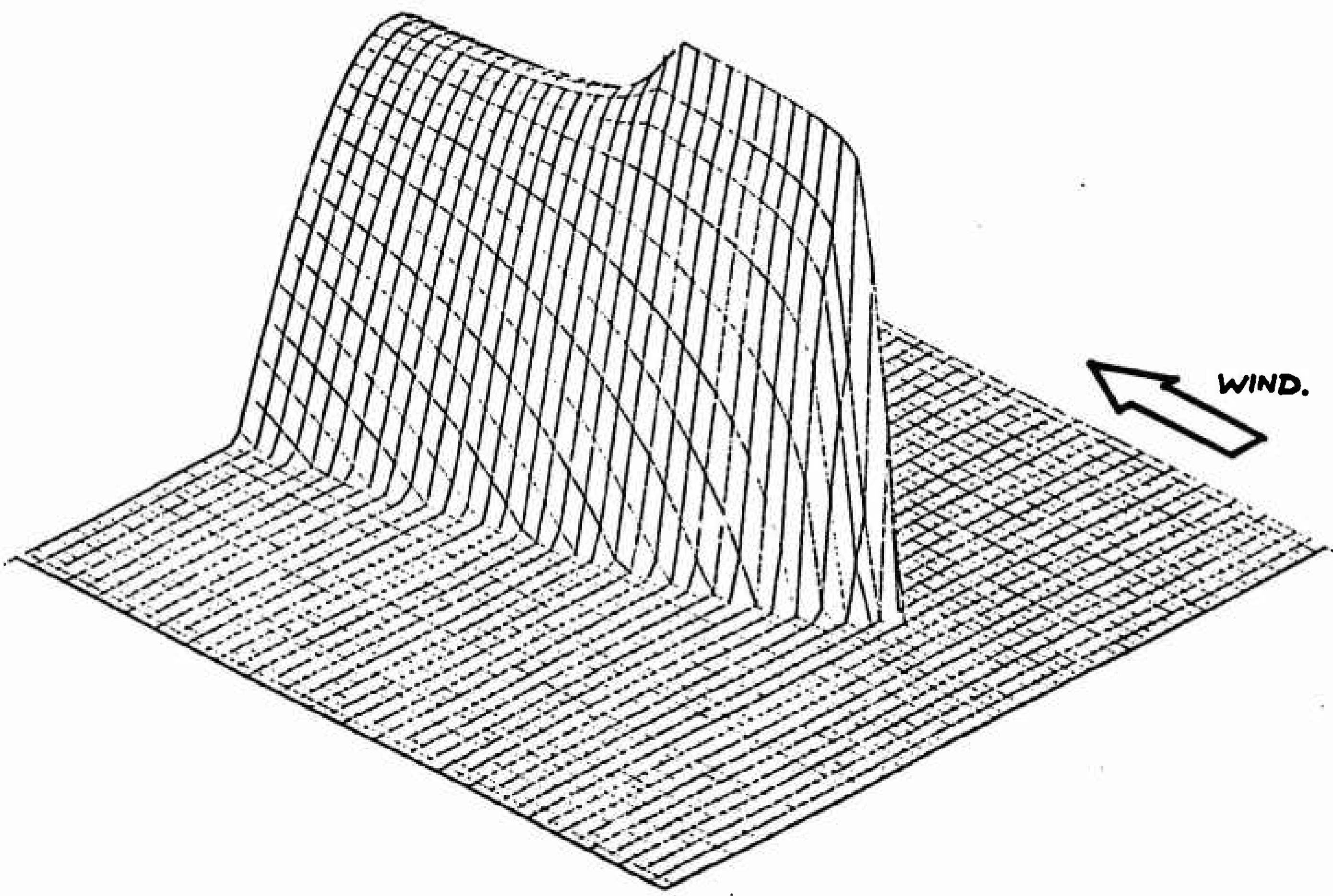


Fig. 5. Isometric Plot of $Log_{10}[X_{CO}]_{ppm}$ for Flight Operations Only [A's of Figure 1]. Peak Concentration is 0.03 - 1 ppm.

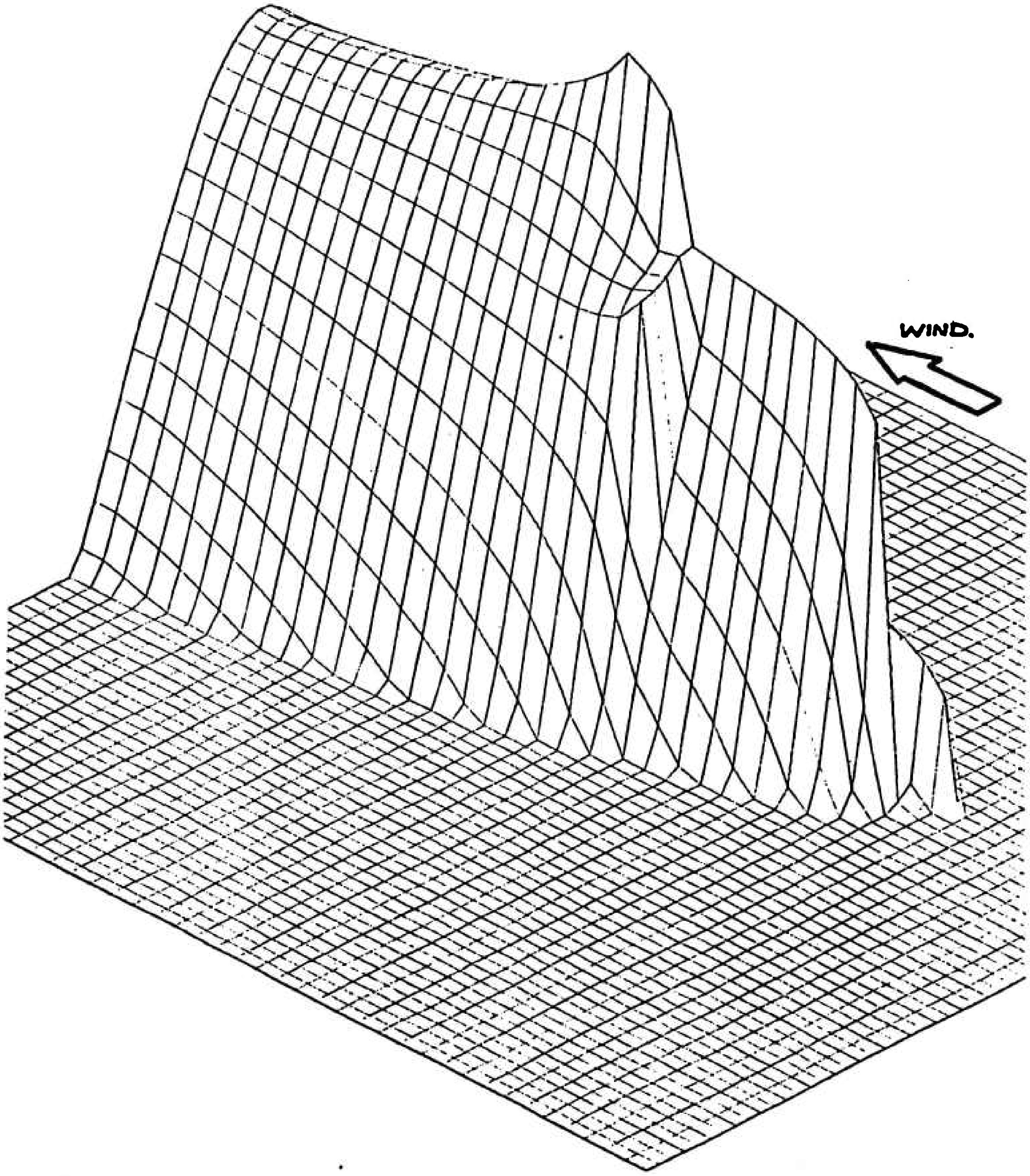


Fig. 6. Isometric Plot for Same Condition as 2a and 2b, but Computed by the Time-Dependent Model [See Section 5.2] with $\sigma_x = \sigma_y = 3.6 \times 10^{-5}$ Km^2/sec and $\sigma_z = 1.6 \times 10^{-5}$ Km^2/sec, and Total Simulation Time of 0.7 hour. Peak Concentration is 3 - 10 ppm.

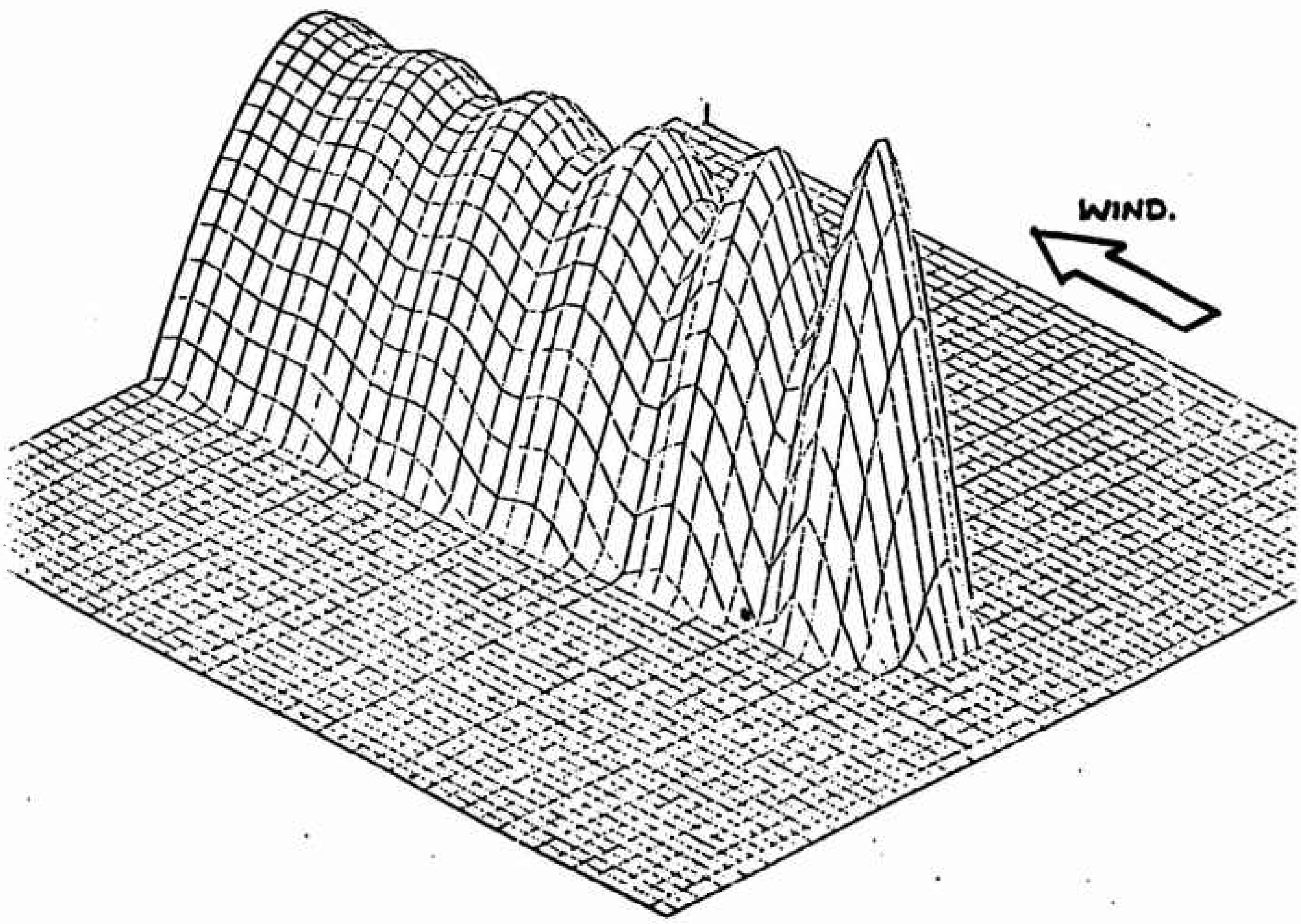


Fig. 7. Isometric Plot for an Intermittent Point Source of 1 Kg/sec Having 1/7 Duty Cycle. North Wind, 10 Km/Hr., $\sigma_x = \sigma_y = 3.6 \times 10^{-5}$ Km^2/sec, $\sigma_z = 1.6 \times 10^{-5}$ Km^2/ sec, $\tau = 0.5$ hr.

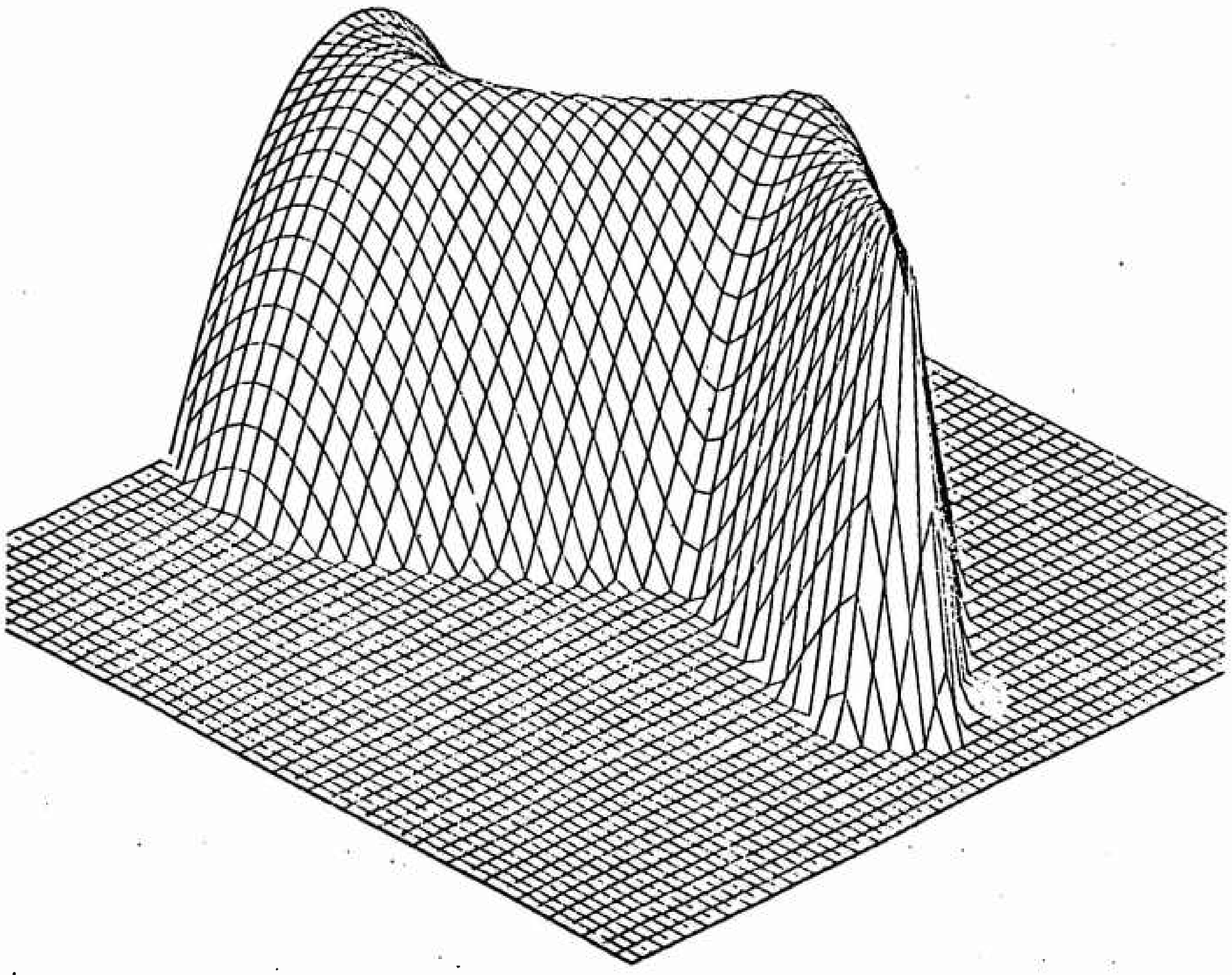


Fig. 8. Isometric Plot for a Point Source of 1 Kg/sec with Oscillatory Winds of 10 Km/hr; $\sigma_x = \sigma_y = 3.6 \times 10^{-5}$ Km^2/sec, $\sigma_z = 1.6 \times 10^{-5}$ Km^2/sec, $\tau = 0.5$ hr.

TABLE 3

TABLE OF INSTRUMENTS FOR POLLUTION MEASUREMENTS†

POLLUTANT	NUMBER OF INSTRUMENTS	INSTRUMENT	MAXIMUM SENSITIVITY FULL SCALE	CHARACTERISTIC TIME	ACCURACY	REPRODUCIBILITY	LINEARITY
CO	2	Gas chromatograph with catalytic conversion and CO to methane flame ionization detector Beckman Model 6800	1 ppm	5 minutes (cycling time)	5% at 1 ppm [dependent on accuracy of standard gas]	0.5% full scale*	1% full scale*
Hydrocarbons	Same instruments as above	Methane and total hydrocarbons detected separately Beckman Model 6800	"	"	2% at 1 ppm [dependent on use of NBS standard]	"	"
NO_x	1	Coulometric titration with iodine conversion Beckman Model 909	0.2 ppm	Continuous 10 minute 90% response	Manufacturers value 5% of full scale for NO_2. Gas standards may not permit this	4% full scale*	
Particulates	2	Tape sampler High air volume Unico Model 80TS-1		0 - 2 hours integrating	No standards known		

* Manufacturers Specification.

† Each instrument was selected to meet the required specifications. Where more than one instrument was available the choice was made on the basis of a survey of users. Each of the instruments listed above was found to be reliable.

Since the CO is probably not involved in photochemical reactions in the lower atmosphere, it serves as a particularly good tracer for transport measurements. We will use a gas chromatograph to measure CO (Beckman, Model 6800). The CO will be converted to CH_4 by catalysis and the resulting CH_4 will be meased by flame ionization. Full scale deflection on the most sensitive scale will be caused by 1 ppm. It is the need for high sensitivity which rules out the use of the non-dispersive infrared CO detectors. Because diffusing CO concentrations fall off rapidly with distance (x) from the source ($\sim e^{-x^2}$) separable concentration contours must be effectively logarithmic. Since most CO measurements are likely to fall in the range 1-10 ppm, only 2-3 contours can be resolved. Thus an instrument having a linear sensitivity of 50 ppm full scale such as the infrared detectors (Beckman IR315A, MSA200LIRA) and a measurement uncertainty of $\sim$ 1 ppm, from scale limitations alone, introduces 100% uncertainties in the lowest contour.

The two main sources of CO, idling and taxiing aircraft and internal combustion engine emissions from airport automobile traffice, are expected to be comparable. CO emission on aircraft take-off and approach is relatively low.

3.3.2 Hydrocarbons

Methane is a constituent of unpolluted air in concentrations of roughly 1.0 - 1.5 ppm. Larger values may be found near sources of natural gas or decaying vegetation. Thus all measurements of hydrocarbons present as pollutants must take this background into account. Methane is not active in photochemical reactions which produce the eye and respiratory irritations of smog, it is only a minority constituent of automotive exhaust which is a prime source of hydrocarbon pollution. Thus, it is the non-methane hydrocarbons which are of interest in this study.

In metropolitan Washington, D.C., non-methane hydrocarbon concentrations averaged about 0.6 ppm for a number of months in 1968[11].

The concentration in the vicinity of Dulles International Airport is expected to be smaller.

Hydrocarbons will be measured using the Beckman (Model 6800) gas chromatograph with flame ionization detection. The method which will be employed involves the separation of methane from one gas sample and its measurement in the flame ionizer. The total hydrocarbons are then measured, from a second gas sample, in terms of equivalent methane. The non-methane hydrocarbon concentration is then obtained by subtraction. The chromatograph can be used in an alternate manner by eluting the methane from the chromatograph column, backflushing and measuring the backflushed hydrocarbon concentration. This latter technique is presently less reliable but may be improved in time for for adoption in this study. It should be mentioned that the gas chromatograph can be used to separate certain hydrocarbons such as propane. The use of propane as a tracer gas will be mentioned later in this proposal. The gas chromatograph has greatest full scale sensitivity for hydrocarbons of 1 ppm.

3.3.3 Particulates

The particulates of greatest interest here are carbonaceous particles emanating from jet exhausts, and carbonaceous and other particles from the exhausts of internal combustion engines. Black particles can be observed in a soiling index test. The arithmetic mean of the soiling index in Alexandria, Virginia in the period April through June of 1967 was 0.3 cohs per thousand linear feet. A measure of the total suspended particulates in the same place for February to August 1967 was 70 $\mu g/m^3$ taken with a high volume samper[10]. High-volume-sampler measurements taken in the vicinity of Dulles International Airport by the Fairfax County Air Pollution Board were in the vicinity of 48 $\mu g/m^3$[12].

For the modelling purposes discussed here, once-a-day sampling with the high-volume technique accompanied by a time delay in processing

the samples make high volume samplers inappropriate. A tape sampler with a high flow rate allows more rapid sampling. The tape sampler chosen, a Unico Model 80TS-1, has a full rate of 0 - 1 cfm.

3.3.4 Oxides of Nitrogen

Two oxides of nitrogen are generally considered as compounds of the clean, natural atmosphere, N_2O (0.5 ppm) and NO_2 (0.02 ppm)[13]. The former is inert for our purposes, but the latter enters into hydrocarbon reations which result in irritating aldehydes and peroxides. Two oxides are found from exhaust gases, NO and NO_2; the NO is slowly oxidized to NO_2 and the NO_2 may then react or may be photolized to reform NO. The oxides of nitrogen which will be measured in this work will be NO and NO_2; they will not be differentiated; the measurements will be recorded in terms of an equivalent amount of NO_2.

The arithmetic average of the NO_2 concentrations for the years 1963-1967 at the Washington, D.C. CAMP station was 0.037 ppm, and that at Alexandria, Virginia, not far from Washington National Airport, was 0.02 ppm for six months of 1967. Concentrations of NO are expected to be somewhat smaller. These figures demonstrate the need for very sensitive instruments, particularly in the relatively unpolluted atmosphere near Dulles International Airport. We will use a Beckman Model 909 coulometric analyzer modified to measure both NO and NO_2. With this instrument, NO is oxidized to NO_2 which is analyzed coulometrically by the oxidation of iodine. A full scale sensitivity of 0.2 ppm allows detection of NO_2 down to background levels. Source interference is possible from ozone, SO_2, H_2S, mercaptans and ammonia at 1 ppm levels. It is expected, however, that 1 ppm levels of SO_2 or O_3 (levels of high air pollution) will be accompanied by higher oxide of nitrogen levels and no important error will occur. Levels of the other pollutants are unlikely to approach 1 ppm.

Two values are given in Table 3 for the estimated accuracy of measurement of each pollutant. The first is from manufacturers specifications. The second is determined from an estimate of the accuracy of available standard mixtures containing the required gases in concentrations of about 1 ppm. Methane is presently available from the NBS, but CO and nitrogen oxides are not.

3.3.5 Meteorological

Transport of pollution is governed by winds, turbulence, and thermal gradients. These must be measured in forms suitable for input into a mathematical dispersion model.

Meteorological instrumentation is now maintained at both Dulles and National Airports. Radiosondes are released twice a day by the Weather Bureau, seven days per week at Dulles, and five days per week at National. Observations have shown that inversions occur below 500 feet for about 30% of the time near the city, and about 35% near Dulles. Major stagnation is expected at least once per year between August and October.

We will supplement current airport sensors with four sets of meteorological instruments, listed in Table 4. These will be deployed to probe horizontal gradients of temperature and wind direction and speed. Because understanding the important phenomena of inversion buildup and decay will be crucial to successful modelling, we will seek to supplement the radiosonde lapse rate data by placing sensors upon existing high structures and buildings, and upon local aircraft. These emplacements will, of course, require the consent of airport authorities and the cooperation of aircraft operators. In any event, a subsidiary model will be constructed to allow interpolation between successive radiosonde flights; and ground-based measurables, such as surface heating rates, will be employed to help infer inversion stabilities.

Table 4. Meteorological Instruments

Instruments	Source	Remarks
Radiosondes	U.S. Weather Bureau	Twice daily (6:15 am and p.m.) at Dulles 7 days per week. Twice daily 5 days per week at National.
Surface wind and temperature	Airport weather station	Hourly or half-hourly at each airport.
*Wind and temperature above ground, and surface wind and temperature (4 sets)	Tower installation by Boeing. Packard Bell (geotech) W/S 101 or equivalent with Boeing temperature sensors.	*Installed at two heights, reading frequency as required, permanent record used in calculations.
*Temperature vs. altitude	Aircraft installation by Boeing.	Recorded in flight, record applied to calculations.

3.4 Instrument Deployment and Model Validation

For model validation, a minimum of 30 days will be chosen for test at each airport during the six-month period. These days will be selected to reflect a suitable diversity of aircraft traffic loads and meteorological conditions at each airport. Emphasis will be placed upon those periods of the year in which meteorological conditions and traffic loads make pollution of the airport neighborhood most likely. First tests of the model will be made at Dulles, since the complications of background contamination are less. However, care will be taken not to bias the selection of days so that unrepresentative data are obtained at Washington National.

The pollution measuring equipment will be deployed in two sets. One set, mounted in a truck, will consist of the methane total-hydrocarbon CO analyzer, NO_x system, a particle monitor, and meteorological equipment. This set will be termed the mobile set. To prevent contamination by an internal combustion engine it will be powered by batteries with an inverter. A second instrument set will be mounted

* Conditional upon the permission of local authorities.

in a battery equipped trailer, and will consist of a methane total-hydrocarbon-CO analyzer, a second particle monitor, and meteorological equipment. The second set is intended to be semi-mobile, that is, movable daily but not hourly. The two remaining sets of meteorological equipment will be deployed at the airport or on towers, see Section 3.3.5. All equipment will run automatically.

A typical twenty-four hour measurement period is summarized in Table 5. The weather forecast, data from the morning radiosonde and the local air pollution data and forecast, will be collected by the field measurement team and telephoned to Seattle for insertion into the model. Sets of pollution contours will be computed for the observing period ahead. (Particular attention will be given to changes in stability conditions and to the predicted appearance of fumigation events.) These contours will be functions of the air traffic (which can be predicted from schedules and records), wind, and stability information. From the contours, a set of instructions for apparatus placement and duration of measurement in each location will be developed and telephoned to the measurement team located at the airport. In addition, the measurement team will have a set of maps and instructions representative of many conditions, in case sudden changes in conditions invalidate telephoned instructions.

Several hours before measurements begin, equipment will be checked and warmed up by a technician experienced in the use of all the instruments. The semi-mobile set will typically be downwind of expected high pollution sources, and will serve as a monitor of source strength during periods of relatively unvarying stability and wind speed and direction. The mobile set will make traverses according to prescribed directions. These traverses will define the emission path and determine concentration gradients. The CO-hydrocarbon analyzer samples about once every five minutes, and a number of samples is required at each location to allow averaging over wind fluctuations. Thus, measurements will be

TABLE 5

Twenty-Four Hour Measurement Schedule
(*Reposition refers to a major relocation and not to movement of the truck-mounted instruments.)

Washington Time	Washington Function	Seattle Function	Seattle Time
7 am	COLLECT DATA		4 am
8	TRANSMIT METEOROLOGICAL DATA	FORECAST	5
9	REPOSITION*	INSTRUCT	6
10			7
11			8
12			9
1 pm	MEASURE		10
2			11
3			12
4	COLLECT AND TRANSMIT DATA	ANALYSE	1 pm
5			2
6			3
7	REPOSITION AND COLLECT DATA	REINSTRUCT	4
8			5
9			6
10			7
11	TRANSMIT DATA	ANALYSE	8
12			9
1 am			10
2			11
3	MEASURE		12
4			1 am
5			2
6			3

made for periods of approximately one-half hour at each location. This time will be kept to a minimum to reduce complications arising from wind shift.

When queuing is expected, ground movements will be monitored by time lapse photography and/or direct observation.

At periods of low activity (11:00 p.m. to 7:00 a.m., at National, for instance) the measuring equipment will sometimes remain at fixed locations operating automatically. This mode of operation will allow measurements to be made on days additional to the minimum stipulated number.

Source strength calibration and model testing can be carried out using a release of the saturated hydrocarbon gas, propane. Propane can be detected using the gas chromatograph flame ionization detector. Propane is colorless, odorless, non-toxic but flammable. Its natural concentration is low and in polluted urban atmospheres is not likely to exceed the Los Angeles value of 0.05 ppm[(11)]. Agreement of the FAA and cognizant local agencies for one or more propane releases will be sought.

Model development will continue throughout the first 9 months of this study. Attention will be paid to the inclusion of wind shear and direction change, the improvement of the stability criteria, and the development of methods for dealing with fumigation. Special effort will be made to improve the model for low wind speed. During the model validation tests, a score will be kept of the deviation of the model predictions from the measurements. This score will be up-dated directly after each test day and will be available to the FAA.

The use of strong feedback from the field will enable the development to proceed on a realistic basis and will insure a well developed model of definable accuracy at the end of the contractual period.

The approach which we propose is labor-intensive, in that it involves three persons in the field through the six-month measurement

period. The short calendar time available for the entire model-validation campaign requires that every measuring day be used to full advantage, and thus that sensors be repositioned at frequent intervals as meteorological conditions fluctuate. Fast computer turn-around is necessary so that sensor deployment can profit from recent observations. The Boeing Scientific Research Laboratories IBM 360/44 is available to the proposed contract with direct access at pre-scheduled times.

3.5 Operational Procedures

The available methods of pollution reduction involve changes in procedures, equipment, and facilities. These changes can be classified into two groups, namely, those having minor and those having major impact on ground equipment and facilities.

Minor changes include:

1. Taxiing with two engines instead of four (or three in the case of tri-jets).
2. Diluting peak pollution emissions by spreading aircraft movement peaks.
3. Eliminating the practice of dumping engine shutdown fuel drainage in the atmosphere shortly after take-off. (1 - 1½ quarts per engine can accumulate in the engine fuel drain sump, depending on engine model.)
4. Installing emission reduction devices on ground servicing vehicle engines (GPU, air conditioning, engine start, toilet, water, galley and cleaning trucks, cargo/baggage handling vehicles and loaders, fuel trucks/hydrant trucks, PAX handling vehicles).

Changes which would have a major impact on ground facilities include:

1. Towing aircraft from the terminal to a holding area near the take-off position using conventional tow tractors.

2. Towing with weight transfer vehicles.
3. Underground cable haulage systems for moving aircraft.

In order that the merit of these changes may be assessed in terms of both their reduction in pollution and cost-effectiveness, the general case of airplane movement between the ramp and the runway will be studied, account being taken of the following factors:

1. The distance between the gate and the runway
2. Local conditions at the gate
3. Simultaneous arrivals and departures
4. Average number of aircraft awaiting take-off at peak periods
5. The jet-wake velocity and noise levels associated with the increased power settings necessary if all the engines are not used for taxiing. This mode of operation will reduce CO emission at a rate faster than the fractional decrease in engine number, however, more nitrogen oxides may be emitted.
6. Alternate methods of moving airplanes (i.e., conventional tow vehicles, weight transfer vehicles, friction drive machines, underground cables or chains, etc.).

Present tow vehicles may be used for airplane movement; however, these vehicles are not designed to tow maximum taxi weight aircraft at speeds much above 5 mph. Consequently, the time required to move an airplane, say 1½ miles from the gate to the runway, would ordinarily be excessive. However, for certain airports at peak periods when airplanes are stacked, the conventional tow vehicles will be acceptable. Indeed, the slower ground movement will actually assist in dispersing the aircraft.

New low pollution types of ground drive systems will be considered. These will be expensive. However, major cost offsets might be obtained to credit against increased capital expenditures. For example, the estimated fuel cost for approximately 134,000 ground taxi hours

(estimated major airline annual fleet statistics) is in excess of $\$7 \times 10^6$ (1.34×10^5 x 470 gallons/hr x \$0.113/gallon). Some potential economic advantages of power drive systems internal to the airplane are the elimination of towing and crew costs and of occasional waits for towings, the possibility of more precise spotting, the reduction of accidental damage to the aircraft resulting from towing, a potential reduction of noise and air pollution, the ability to park nose-in without towings and to maneuver in the maintenance hangers, a reduction in engine cycling and fuel costs, and a reduction in take-off weight arising from queuing fuel uncertainties.

Some disadvantages of an internally powered surface drive system are the equipment and installation costs including additional auxiliary power unit (APU) capacity when required, costs arising from delays pursuant to APU failure, and the additional flight weight of the system. Past Boeing involvement with ground movement schemes is discussed in Section 7.0.

At present not all aircraft are equipped with auxiliary power units. Consequently, movement with passengers on board by conventional tow vehicles will require alternate methods of providing cabin air conditioning and other necessary services. One vehicle which has been in various stages of design for several years includes all necessary pneumatic, hydraulic, and electrical power. This vehicle has been designed to move aircraft at taxi speeds of 20 to 30 mph. Its use will be considered. However, for existing aircraft, significant problems will be experienced in providing the necessary attachment or interface point between airplane and tow vehicle.

It is necessary that the implementation of changes recommended to reduce air pollution create minimal interference with the future growth of airports. We will, therefore, consider changes in the context of overall airport plans including projected airline utilization.

We will also take account of the fact previously mentioned, that automotive operations account for a significant fraction of the total airport pollution.

4.0 Problem Areas

Major problem areas may be divided into three sections: calculational (4.1), experimental (4.2), and a final section involving areas where iteration procedures between calculation and measurement may be used to advantage (4.3).

4.1 Calculational Problems

Although plume models have been developed over a number of years to yield relatively good predictions under conditions of steady wind, models for conditions of very low wind speeds are not as reliable. It is in periods of low wind speeds that high pollution levels occur. Thus, considerable effort will be devoted to the low wind speed conditions. The second of our trial models (Section 5.2) has the best potential for accuracy with low winds.

A second calculational problem occurs when fumigation is under discussion. Only crude theories have been formulated of the mixing processes which take place during fumigation. In applying such theories we depend upon the model used to predict the pollutant distribution existing before fumigation. Thus errors in both the diffusion and the fumigation models contribute to errors in the final result.

Thirdly, we must ask to what extent does a useful time interval exist during which steady-state descriptions are appropriate. To answer this question, both steady-state and time-dependent models will be used in parallel computations and quantitative comparison will be made between them. Score functions and score keeping are indispensable

parts of the proposal effort. Fluctuation distributions and moments will be measured, reported, and discussed.

4.2 Experimental Problems

Deviations from schedules, operations involving non-scheduled aircraft, field movements which involve no flight, and variations in the taxiing and idling procedures make the use of airline schedules only a first step in compiling a useful inventory. It will be the duty of the measurement team to maintain a valid inventory by direct observations and with the use of time-lapse photography. A check on the source inventory can be obtained from absolute measurements of the various pollutant concentrations, but this check is only as good as the model. A test of the model is proposed involving the release of propane, see Section 3.4.

A second experimental problem is meteorological. Ground level wind and temperature data should be adequate, but data on wind shear and direction change, and temperature lapse, needed to supplement the daily radiosonde data, will necessarily be obtained from such towers and aircraft soundings as can be arranged. The location and choice of suitable mountings will be one of the first tasks to perform on the contract.

4.3 Interaction between Measurement and Models

In order that the model predictions be available to the measurement team early enough to influence the placement of the instrumentation we shall keep the time for a complete data processing cycle (data transmittal to Seattle, model computation, and reply to Washington D.C.) to about four hours.

The question of the optimum integration time for the measurements has been raised. In specific instances the best answer can be obtained

by combining observation with calculation. For example, it may be that some measurements (wind velocities and directions) can be made more frequently than others (pollution concentrations). In such cases the meteorological data will be used to adjust the model incrementally and thereby to provide pollution concentrations throughout the integration period. The signal-to-noise ratio of the less frequently measured variables can then be enhanced by cross correlating the measurements against the model. By this technique the precision of fitted variables, such as σ_x and σ_y of the Gaussian plume models, can be increased by averaging over discontinuous segments of observing time.

Finally, the transport parameters σ_x, σ_y (or S_x, S_y, S_z), defined on pages 34, 36, will be determined by three independent methods:

1. By best fitting the measured contours to the computed models.
2. By statistical analysis fo wind-field fluctuations, and
3. From Turner's tables[6].

We will test our expectation that method 2. gives better agreement with method 1., than does method 3.; this being so, *a priori* transport parameters from wind field fluctuations will be accepted as standard.

5.0 A More Detailed Discussion of the Mathematical Models

Two air-quality dispersion models have been constructed, and adapted into a form suitable for estimating pollutant concentrations near airports. The first (Section 5.1) is a gaussian-plume integration, a generalization of models widely used for estimating stack-plume dispersion. In the form presented here it is limited to steady-state conditions, both for pollutant source fluxes and for wind velocities and directions. Inversions, buoyant plume rise, and engine blast are incorporated in a straightforward way. The second (Section 5.2) is a three-dimensional advection-diffusion model with which non-steady sources and winds can be treated. Treatment of inversions, plume rise and engine blast are again straightforward. Storage and computer-time requirements for the two models are approximately comparable. A major question to be answered by measurements at actual airports is whether the simpler steady-state model is useful under the important conditions of high pollution resulting from slow, meandering winds.

5.1

A steady-state model has been constructed which computes pollution concentrations by summing contributions from multiple point sources, according to the gaussian plume equation:

$$C[X,Y,Z] = \sum_k \frac{Q_k}{2\pi\sigma_y\sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \left\{\exp\left[-\frac{1}{2}\left(\frac{Z-k}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+h}{\sigma_z}\right)^2\right]\right\}$$

where

C = concentration of a particular pollutant (i.e., CO)

X,Y,Z = external Cartesian coordinates

x = internal length coordinate measured downwind from the k^{th} point source

y = internal cross wind coordinate (normal to x)

Q_k = k^{th} point source (K_g/sec) located at external Cartesian coordinates (X_k, Y_k)

σ_y & σ_z are scale factors determining the transverse and vertical spread of the gaussian plume. These are separately assumed to be functions of x, only. For this illustration

$\sigma_y \cong 0.1 + 0.1\ x^{0.8}$ kilometers

$\sigma_z = 0.03 + H[1 - \exp(-0.06\ x/H)]$

$H = H \rightarrow$ inversion altitude (km)

These expressions have been fitted to Turner's empirical table(6), corresponding to his stability class "C". The form of the equation for σ_z gives the "correct" (Turner's) behavior in the limit $H \rightarrow \infty$, and smoothly truncates σ_z to equal H at large x. This is just a simple way of inhibiting vertical mixing in the presence of inversion at H.

u = the wind velocity (km/sec)

h is a parameter measuring the altitude of the center of the plume. This equals the altitude of emission δ_o plus the buoyant rise, δ.

Fay(2) has given a simple analysis from which at time greater than τ:

$$\frac{\delta}{\ell} \cong \left(\frac{t}{\tau}\right)^{2/3} = \left(\frac{x}{u\tau}\right)^{2/3}, \quad \text{where} \quad \ell(\sim 30\ \text{m}),\ \tau(\sim 30\ \text{sec}).$$

We choose to modify δ for effects of a finite mixing layer below an inversion at H, in a manner similar to that for σ_z:

$$\delta = \frac{H}{2}\left\{1 - \exp\left[\frac{-2\ell}{H}\left(\frac{x}{u\tau}\right)^{2/3}\right]\right\}\text{km}$$

An approximate correction for horizontal source-deplacement due to entrainment by the jet exhaust can also be derived from a simple extension of Fay's treatment: the distance behind a jet where the exhaust becomes essentially stationary is

$$L = v_o\tau\left[\frac{\pi b_o}{3\alpha\ell}\right], \qquad \text{where}$$

v_o is the jet exhaust velocity at the plane of effective expansion behind the nozzle,

b_o is the effective radius of the exhaust at the expansion plane,

and

$\alpha \cong 0.15$ is dimensionless constant.

Table 6 gives a short summary of these parameters for two common engines.

TABLE 6

Airplane	Engine	v_o^*	b_o	L
707	JT3D	$0.37 \frac{km}{sec}$	0.6 meter	1.6 km
747	JT9D	0.24	1.0	1.7

*Full thrust at sea level

This L-displacement occurs in a time on the order of τ . Therefore dispersion calculations at times greater than τ can approximately account for jet entrainment by a simple coordinate shift of the source function to virtual sources displaced L behind the full thrust aircraft. For aircraft at reduced thrust for idle or taxi, L will usually be less than the spatial resolution of the model, provided these aircraft are not in the entrainment zone of other planes at full thrust. This will not always be the case, however.

Figures 1 to 8, given on pages 9-17, illustrate carbon monoxide concentration contours computed for a simulated runway, taxi and service area, and queue of idling airplanes.

5.2 A time-Dependent, Advection-Diffusion Transport Model for Air-Quality Studies

During conditions of greatest pollution buildup, wind speeds are low and variable and wind directions are eratic. A Gaussian distribution of wind speeds is unrealistic. Similarly, because sequences of wind directions are often circulatory, and not oscillatory about a mean, a Gaussian direction distribution is a poor representation of actual conditions. For these reasons Gaussian-plume steady-state models are noc well suited to conditions of low wind speed. Consequently, we have constructed a second trial model which can treat arbitrary, time-dependent flows.

This model is a simulation, not an integration; a simplified algorithm is:

1) A three dimensional air-space grid is defined.
2) A three-dimensional pollution flux intensity (which may be time dependent) is defined.
3) A wind direction and speed is defined.
4) A time increment is set equal to a grid dimension divided by the wind speed.
5) An increment of pollution (equal to the source flux times time increment) is added to appropriate grid elements, in three dimensions.
6) The air mass is moved downwind by one grid element, over the whole grid network.
7) The second derivatives of the concentrations are computed, with respect to each of the Cartesian coordinates.
8) The concentrations are permitted to relax diffusively, according to the equation

$$C[x,y,z] = C_0[x,y,z] + \left[S_x \frac{\partial^2 C}{dx^2} + S_y \frac{\partial^2 C}{\partial y^2} + S_z \frac{\partial^2 C}{\partial z^2} \right] dt$$

where the S's are diffusion constants, which are parameters of this model.

To account properly for the lower boundary condition (and the upper too, in the case of inversion) for the lowest (and highest) tier of the grid network, the z-diffusion term is changed to

$$\frac{S_z}{\Delta z} \cdot \frac{C}{\partial z}$$

9) The process is repeated by returning to step 3).

For comparison, Figure 6 shows an isometric plot of $\mathrm{Log}_{10}\, X_{CO}$ computed by this time dependent algorithm with the same source and wind conditions of Figures 2a, and 2b, which were computed by the Gaussian plume. Figures 7 and 8 illustrate the flexibility of the time-dependent model as it treats varying wind-or-source intensities, or wind direction.

6.0 Program Schedule, Reports, and Time Estimates

6.1 Schedule

The proposed program is scheduled for completion 14 months after the contract go-ahead; this time includes the submission and approval of the final report. The schedule for the total program and its individual phases is shown in Figure . A functional organization chart is given in Figure

Task A, Investigation and Model Development, will be conducted in Seattle. M. Doyle and K. G. Robinson will have prime responsibility for the ground systems analysis and recommendations. Drs. Cairns, Harrison, and Schoen will establish an inventory and provide model contours of conditions at Dulles and Washington, and will order, test, and install measuring equipment. It must be stated that instrument delivery times make three months the minimum period required for Task A. The consultants will make their prime contributions during this task.

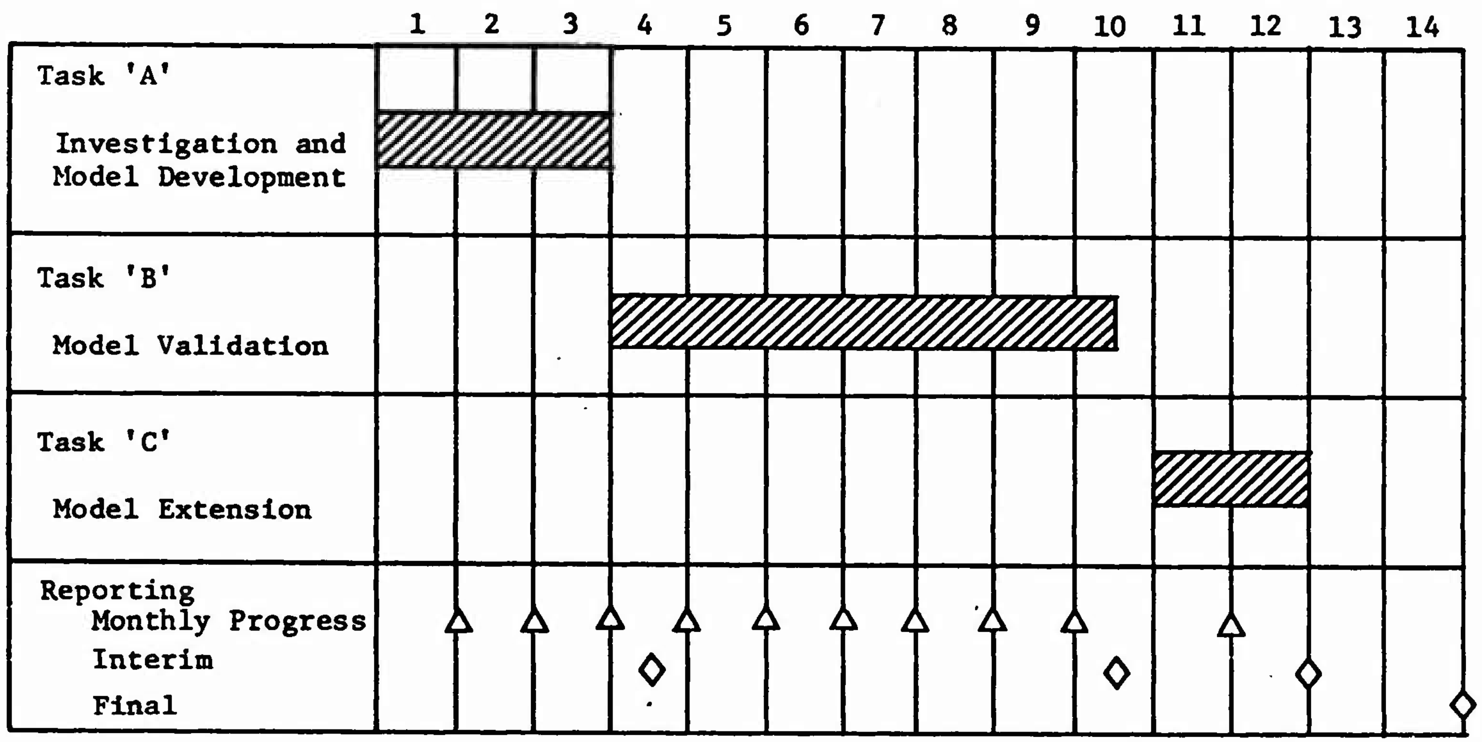
Task B, Model Validation, will involve a measurement team of three persons, resident in Washington. Two members of this team will be from the Boeing, Washington Office and the third will be the Seattle technician experienced in the instrument testing and installation. The Principal Investigator will be in Washington for the initiation of the field program, and will make return visits, as required. Dr. Cairns will retain direct control over the validation measurements.

Task C, Model Extension, will be conducted in Seattle and will involve the science and ground operations personnel, see Figure

6.2 Reports

Monthly, interim, and final reports will be submitted in accordance with the stipulations in the RFP and as shown in Figure . With the

Figure 9 MONTHS AFTER GO-AHEAD



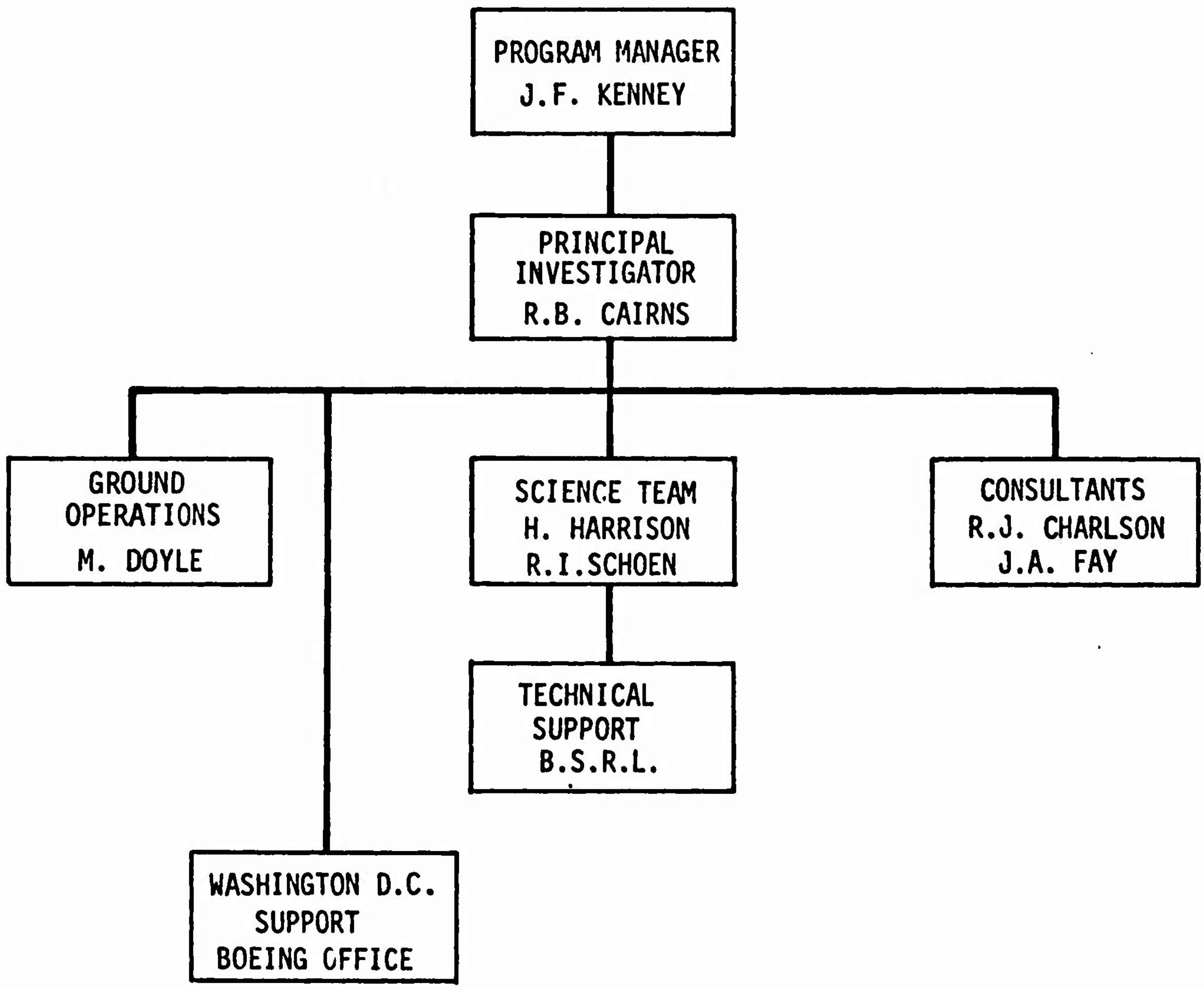

PROGRAM MANAGER
J.F. KENNEY
PRINCIPAL INVESTIGATOR
R.B. CAIRNS
GROUND OPERATIONS
M. DOYLE
SCIENCE TEAM
H. HARRISON
R.I.SCHOEN
CONSULTANTS
R.J. CHARLSON
J.A. FAY
TECHNICAL SUPPORT
B.S.R.L.
WASHINGTON D.C. SUPPORT
BOEING OFFICE

Figure 10

final report, we will deliver complete computer software for the validated program.

6.3 Time Estimates

The hourly time estimates are listed below:

Boeing	Hours
Supervision	955
Professional	3318
General Salary	1431
TOTAL	5704

7.0 Professional Talent, Consulting, and Related Experience

This program will be conducted within the Environmental Sciences Laboratory of the Boeing Scienctific Research Laboratories and will be managed by Dr. J. F. Kenney.

Dr. R. B. Cairns will be the principal investigator working the scientific aspects of the program (modelling and measurement) in collaboration with Drs. H. Harrison and R. I. Schoen. Each of these persons has considerable experience in the fields of atomic and molecular processes, and atmospheric physics (see attached resumés), and has been involved in a small scale experimental study of CO concentrations at Seattle-Tacoma Airport. Dr. Harrison has extensive experience in atmospheric modelling and has written the airport simulation programs discussed and illustrated in this proposal.

Mr. M. Doyle, will contribute to the analysis of ground operations. Mr. Doyle supervises Ground Operations and Equipment requirements for the Boeing models 707/720/727/737 and 747. He has worked with the majority of customer airlines, equipment vendors, airport authorities,

consulting engineers, etc. The following Boeing documents are a partial reference to this activity:

707-720 Jet Transport Planning, D6-1705

727 Facility Planning, D6-7798

737 Facility Planning, D6-17597

747 Facility Planning, D6-14043

Mr. K. G. Robinson is Director of the Air Commerce Research organization. This organization is the focal point within The Boeing Company for all airport related matters. Mr. Robinson will assist in establishing initial contacts, and obtaining study parameters and operating ground rules from the Bureau of National Capital Airports and other specific airport authorities. Special operating procedures which evolve during the study will also be coordinated with the airlines. The Air Commerce Research organization is custodian of an industry-wide airport data bank for the airlines, manufacturers, and airports. These data will be available for this study.

Two consultants will be engaged, Drs. R. J. Charlson and J. A. Fay.

Professor Charlson is Associate Professor of Atmospheric Chemistry in the Department of Civil Engineering, University of Washington. His research interests include aerosol chemistry and physics, and the photochemistry of atmospheric gases.

Professor Fay is at Massachusetts Institute of Technology, a fellow of the American Academy of Arts and Sciences, the American Physical Society, and the American Institute of Aeronautics and Astronautics. In addition, he is Chairman of both the Boston Air Pollution Control Commission and the Jamaica Bay Environmental Study Group of the National Academy of Sciences. Professor Fay has worked directly on the problem of airport pollution.

Competent technical support is available within BSRL including persons experienced in field operations and the collection of meteorological data.

The Boeing Company maintains a Washington office through which good coordination can be maintained between Seattle and Washington, D.C.

RONALD B. CAIRNS

Dr. Cairns received his B.Sc. degree (Honors, 1st Class) in Physics in 1956 and his Ph.D. in Physics (Plasma Physics) from The Queen's University, Belfast, North Ireland in 1959. Since joining the staff at the Boeing Scientific Research Laboratory in 1968, Dr. Cairns has worked on investigations of single and multiple ionization processes in low vapor pressure materials using crossed photon-atom beams, and measurements of relative photoionization cross sections of metastable molecular species. From 1964 to 1968 he was staff scientist, Head Vacuum UV Physics Branch, Experimental Physics Laboratory, GCA Corporation, GCA Technology Division, Bedford, Massschusetts. His research there included a wide range of studies of the interaction of vacuum ultraviolet radiation with matter, i.e., in molecular and atomic gases - photoexcitation, dissociation and ionization processes and resonance and Rayleigh scattering; in solids - reflectance measurements of mirrors and gratings and transmittance measurements of thin metal films, and photoelectric yield measurements. Prior to 1964, Dr. Cairns was employed as a Visiting Assistant Professor at the University of Southern California; a Senior Scientific Officer in the Department of Scientific and Industrial Research, Slough, Buckinghamshire, England; and a Senior Research Fellow (Fellowship awarded by the North Atlantic Treaty Organization) in the Physics Department of the University of Southern California.

Dr. Cairns has published in excess of 44 technical papers and is a member of the American Physical Society.

HALSTEAD HARRISON

Dr. Harrison received his B.S. chemistry degree in 1955, and his Ph.D. in 1960, both from Stanford University. Since becoming a staff member of the Boeing Scientific Research Laboratories in 1963, Dr. Harrison has done experimental work on the energy and angular distribution of photoejected electrons, chemiluminescence, and chemical kinetics, and theoretical studies of atmospheric processes. He has also done extensive Company consulting. Before joining Boeing, Dr. Harrison was a National Science Foundation Fellow at the University of Bonn, Germany; a Research Associate at the University of Michigan; and a staff scientist at General/Atomic/General Dynamics. Dr. Harrison is a member of the American Physical Society and Sigma Xi.

Dr. Harrison has published 18 technical papers.

RICHARD I. SCHOEN

Dr. Schoen received his B.S. applied physics degree from the California Institute of Technology in 1949, his M.S. in physics from University of Southern California in 1954, and his Ph.D. in physics from University of Southern California in 1960. Since becoming a staff member of the Boeing Scientific Research Laboratory in 1961, Dr. Schoen has done experimental work on photoionization including work on electron and ion energy measurements, photoionization of molecular beams, mass spectrometry, and electrically driven shocks. He has also done extensive company consulting on a wide variety of problems including: solar physics, planetary atmospheric problems, spacecraft problems, photoelectric effect from solids, and air pollution. Before joining Boeing, Dr. Schoen was employed as an assistant professor of physics at the University of Missouri from 1955 to 1959. Dr. Schoen is a member of the Executive Committee of Users' Group for Synchrotron Radiation - Physical Sciences Laboratory, University of Wisconsin. He also is a member of the American Physical Society, American Geophysical Union, Association for the Advancement of Science, and Sigma Xi.

Dr. Schoen has published in excess of 22 technical papers and is a co-inventor of U. S. Patent No. 3,397,311 entitled "Broad Beam Mass Spectrometer".

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